

# Axion Solar Telescope Activities: CAST and future prospects

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Lawrence Livermore National Laboratory

# The CERN Axion Solar Telescope (CAST)

- An experimental search for axions created in the Solar interior
- International collaboration started in 1999;
  - 21 institutions from 11 countries, approximately 70 PhD scientists
  - Thesis project for 10 PhD students
- LLNL joins in 2005
- Current science program approved by CERN runs through mid-2011



# What is an axion? (in 70 words or less)

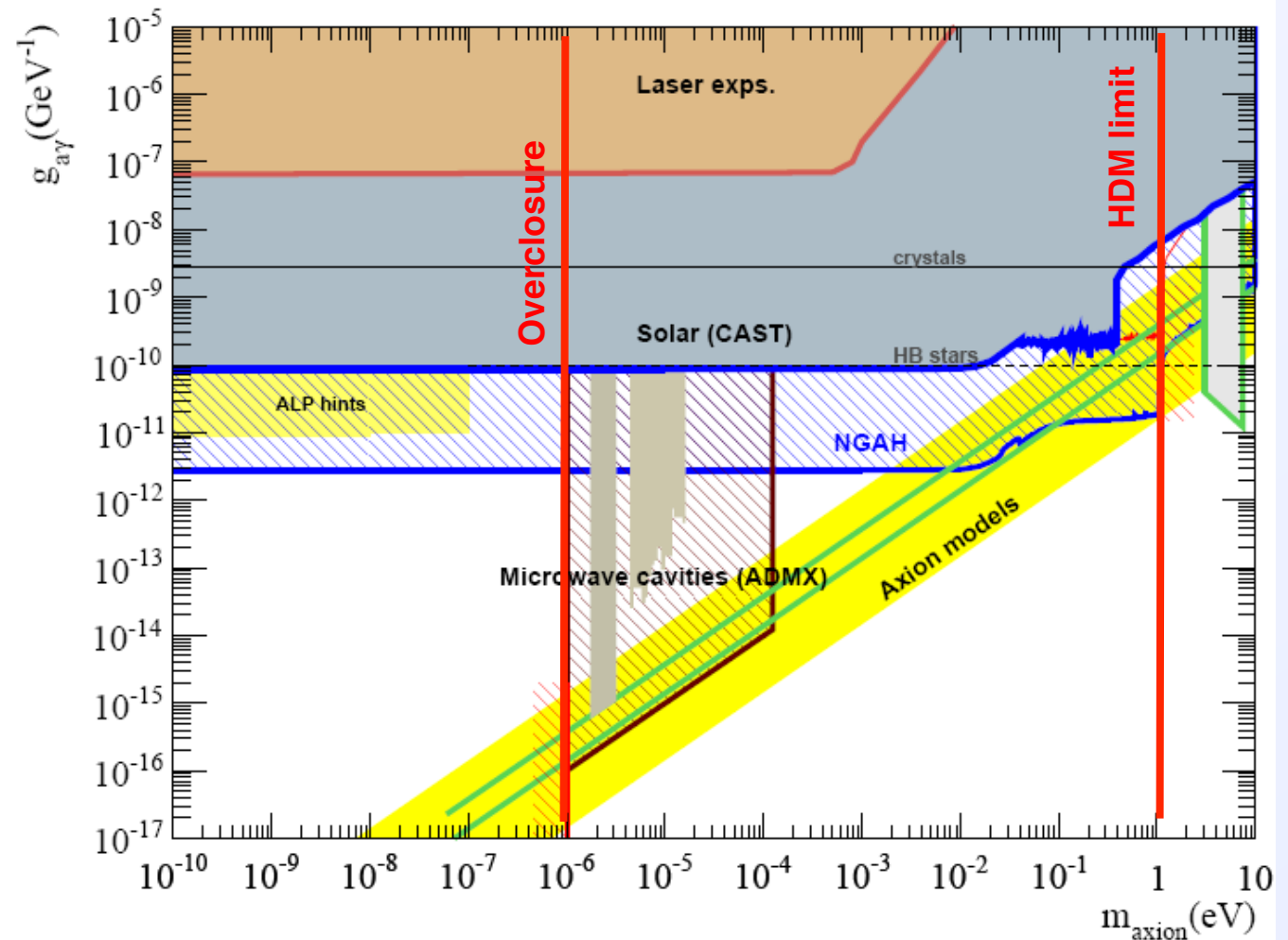
- An axion is an extremely weakly-coupled fundamental pseudoscalar particle (spin-parity,  $J^\pi = 0^-$ )
  - Light, neutral pseudo-Goldstone boson that couples to two photons
  - Potential dark matter candidate
  - Mass unknown  $m_a \propto g_{a\gamma}$
  - Astrophysical constraint  $g_{a\gamma} \lesssim 10^{-10} \text{ GeV}^{-1}$
- Results from a possible solution to the Strong CP problem
- Dubbed the axion by Frank Wilczek
  - *“I named them after a laundry detergent, since they clean up a long standing problem in theoretical physics.”*

Wilczek *PRL* 40:279 (1978)



# Where to look for axions?

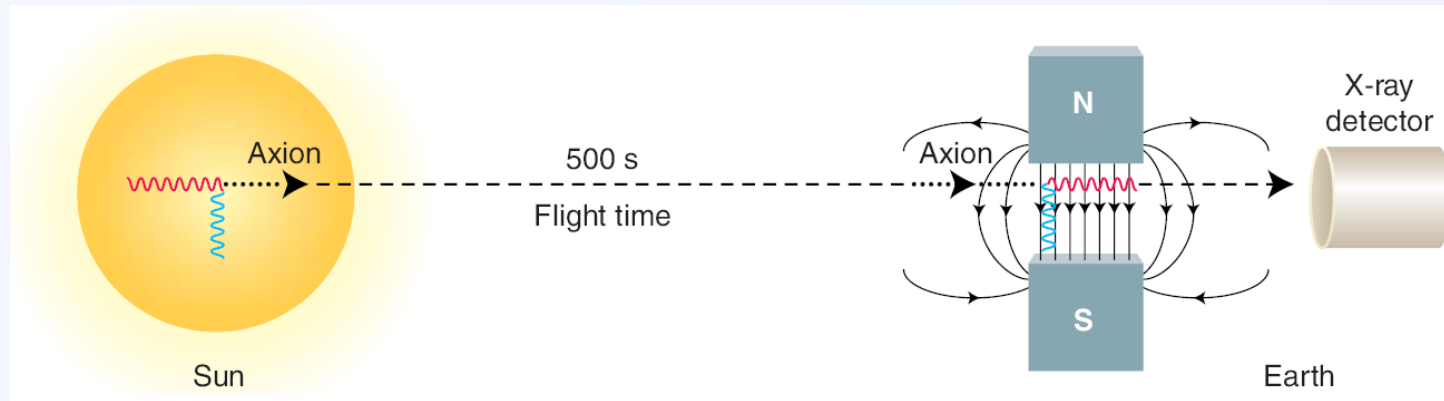
- **Galactic/remnant axions**
  - Haloscopes (ADMX)
- **Laboratory axions**
  - Shining-Light-through-Walls (OSQAR, LIPSS, ALPS)
  - Polarization (PVLAS)
- **Solar axions**
  - Crystals (SOLAX, COSME)
  - Helioscopes (CAST)



# The axion helioscope—basic idea

- Pierre Sikivie first proposed the “axion helioscope”

Sikivie *PRL* 51:1415 (1983)



$$\gamma + \gamma^* \rightarrow a$$

$$a + \gamma^* \rightarrow \gamma$$

- keV x-rays in Stellar core converted into axions via Primakoff effect
- Use a strong, laboratory-based magnetic field to reconvert the axions back into x-rays

# Helioscope conversion details

Conversion probability

$$P_{a \rightarrow \gamma} = \left( \frac{B g_{a\gamma}}{2} \right)^2 \frac{1}{q^2 + \Gamma^2/4} \left[ 1 + e^{-\Gamma L} - 2e^{-\Gamma L/2} \cos(qL) \right]$$

Momentum transfer

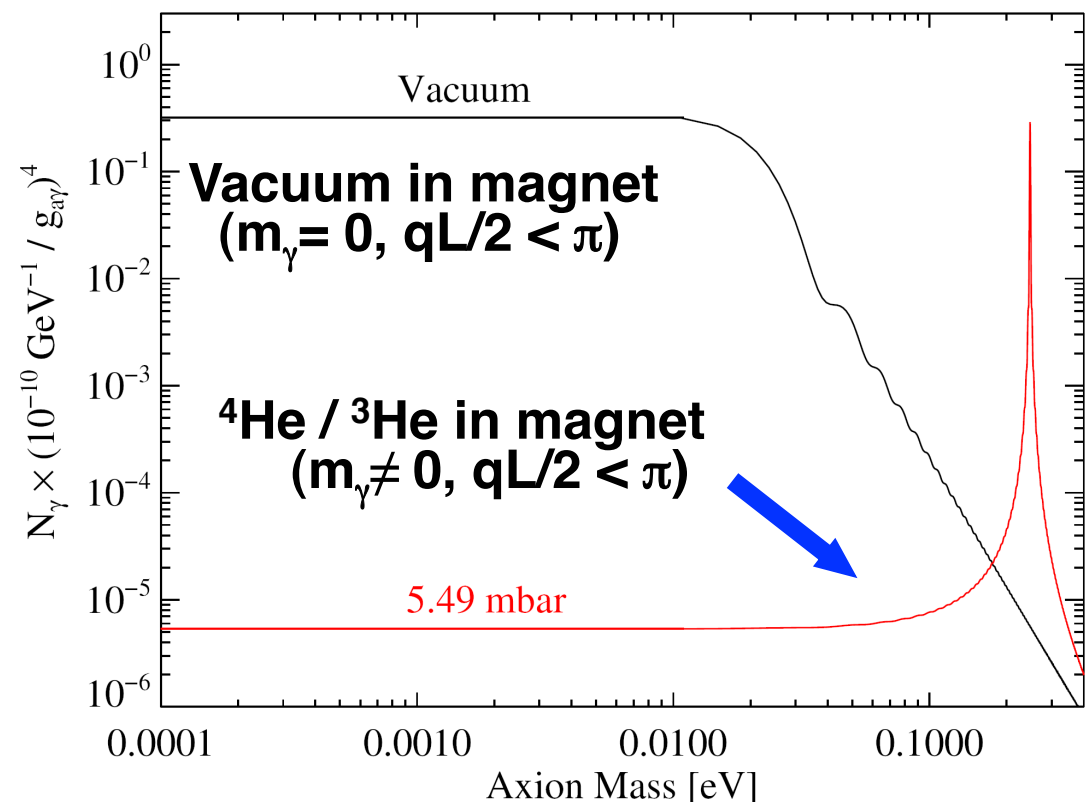
$$q = \left| \frac{m_\gamma^2 - m_a^2}{2E_a} \right|$$

Coherence when  $qL/2 < \pi$

- Van Bibber recognized using a conversion gas would maintain coherence over a long magnetic field, and allow a search for higher masses

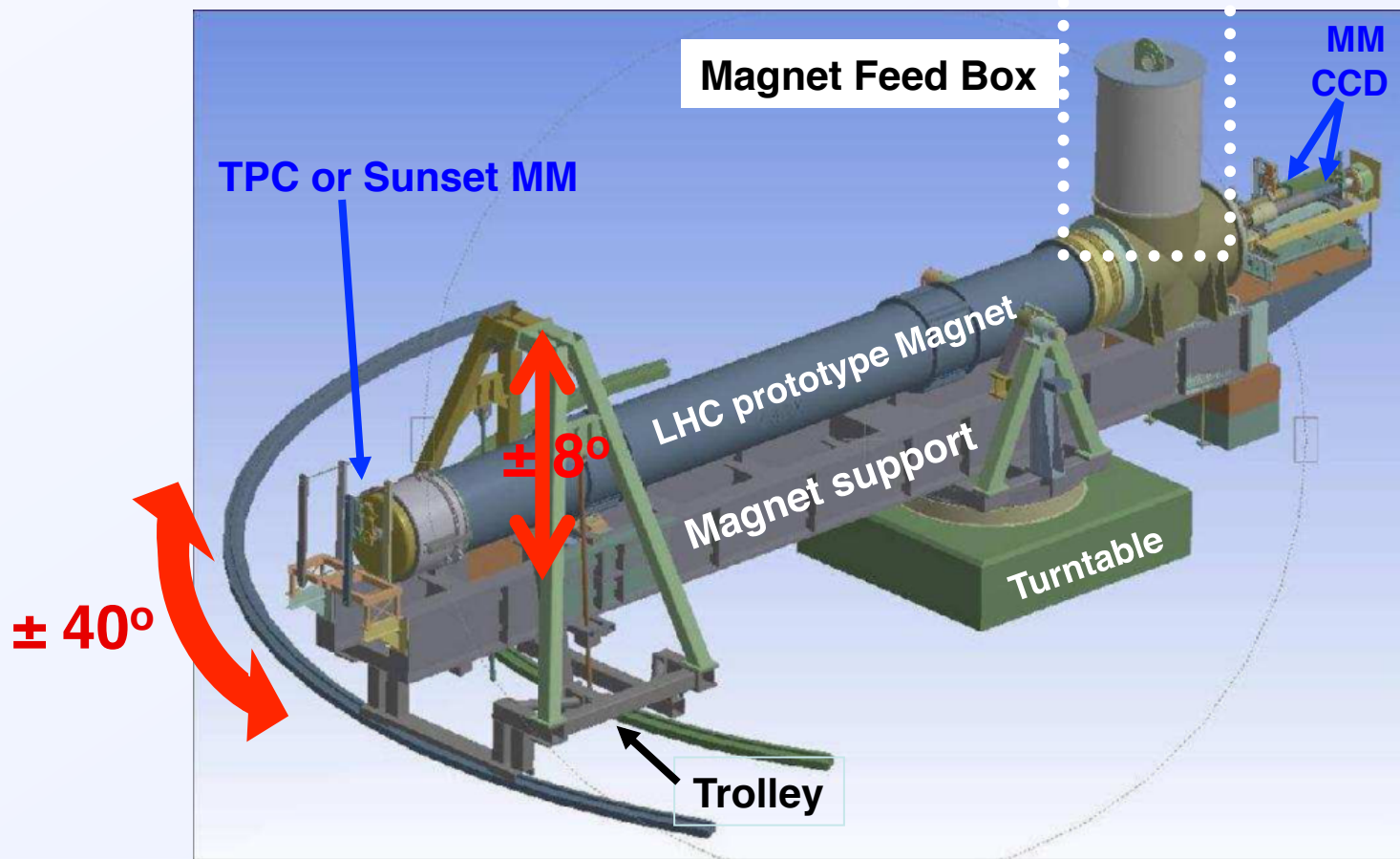
Van Bibber et al.  
*PhysRevD* 39:2089 (1989)

LLNL-PRES-470254



## CAST instrumentation

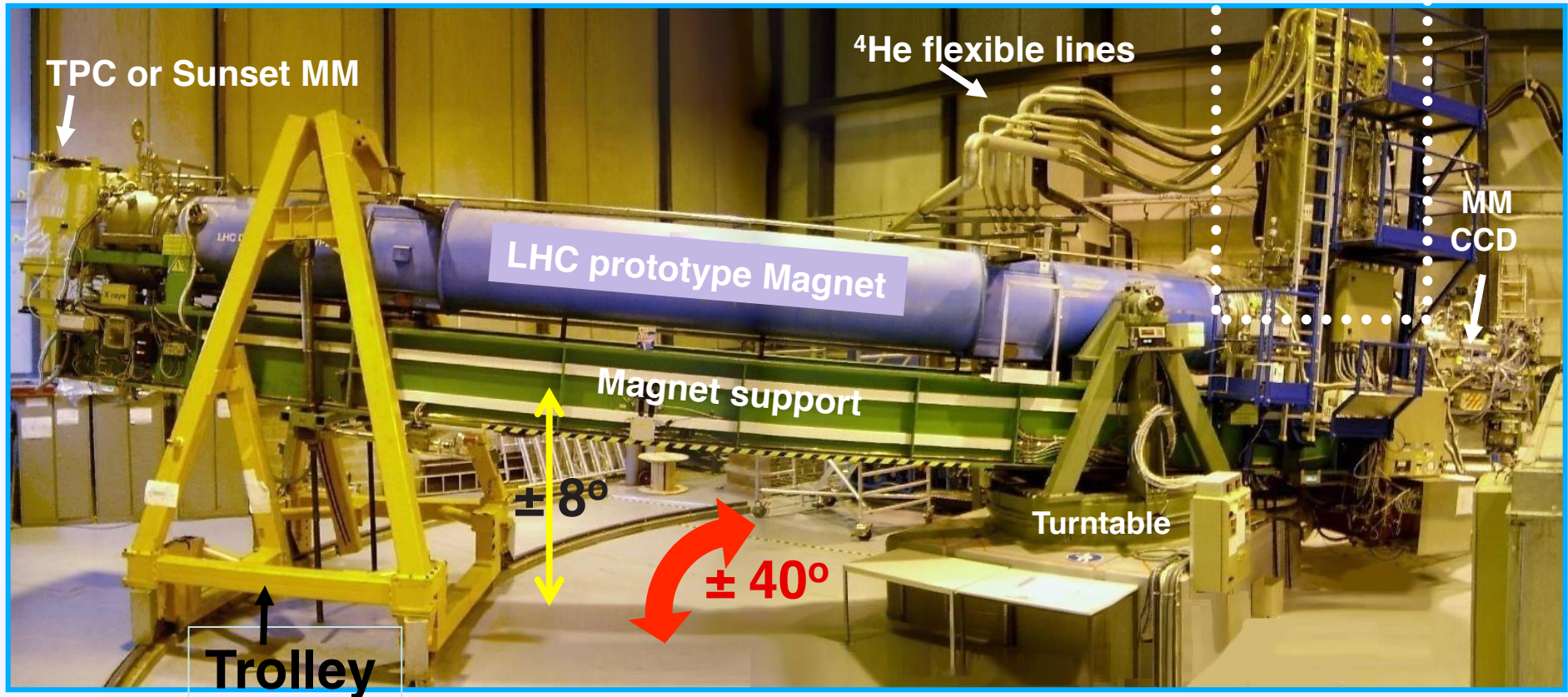
# Cern Axion Solar Telescope





# CAST instrumentation

## Magnet Feed Box



### Sunset detectors (both bores)

Time projection chamber (2003-2006)  
Micromegas (2007 onwards)

### Sunrise detectors

1 bore: X-ray CCD + telescope  
1 bore: Micromegas detectors





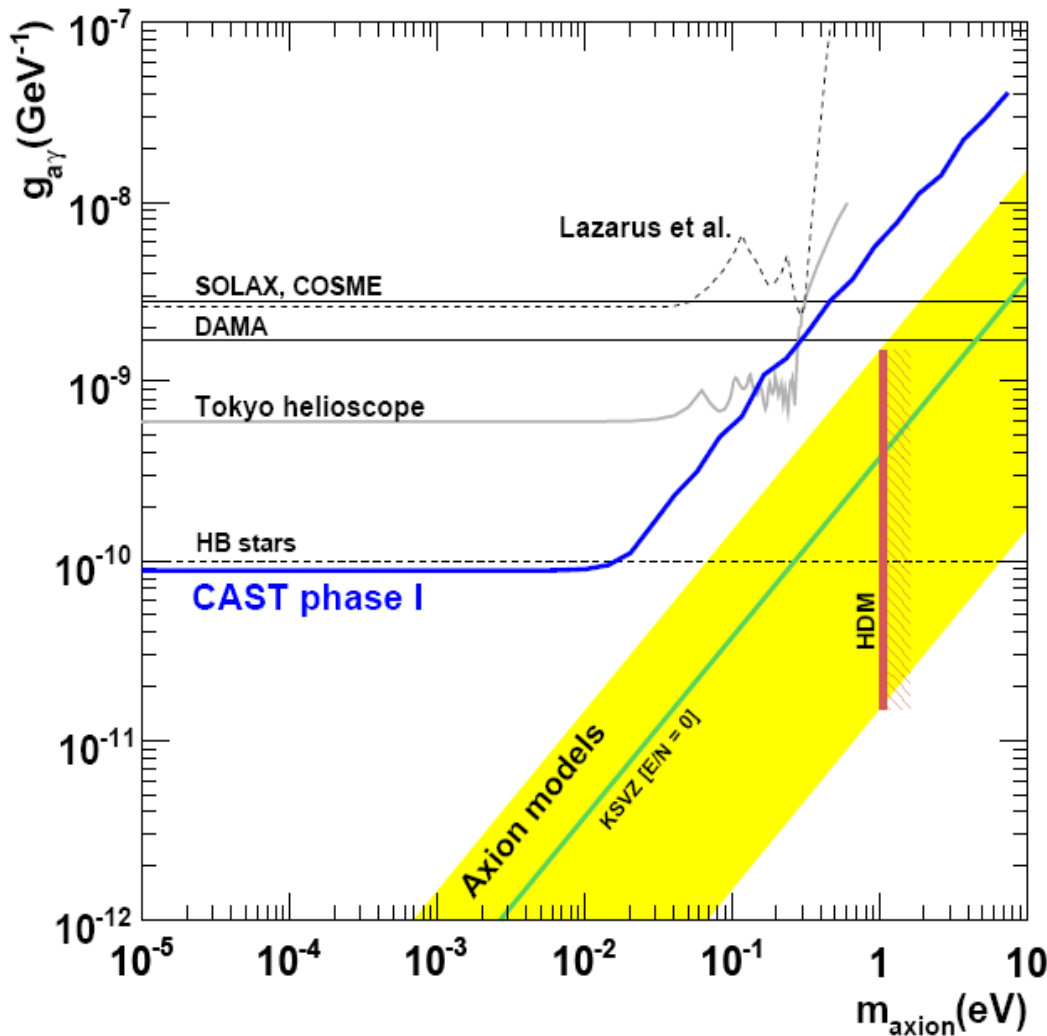
# CAST physics program

- CAST Phase I
  - Vacuum operation, completed during 2003 – 2004
  - Sensitivity up to  $m_a \approx 0.02$  eV
- CAST Phase IIa
  - $^4\text{He}$  gas in bore, completed during 2005 – 2006
  - 160 different pressure settings, up to 13.4 mbar
  - $0.02 < m_a < 0.39$  eV
- CAST Phase IIb
  - $^3\text{He}$  gas in bore, started in late 2007
  - Several hundred pressure settings, up to 120 mbar
  - $0.02 < m_a < 1.2$  eV
- Visible and high-energy axions (not discussed today)



# CAST Phase I results

Andriamonje et al. JCAP 0704:010, (2007)



## Phase I: (2003 – 2004) vacuum operation

$$g_{a\gamma\gamma} < 8.8 \times 10^{-11} \text{ GeV}^{-1} \quad (95\% \text{ CL})$$

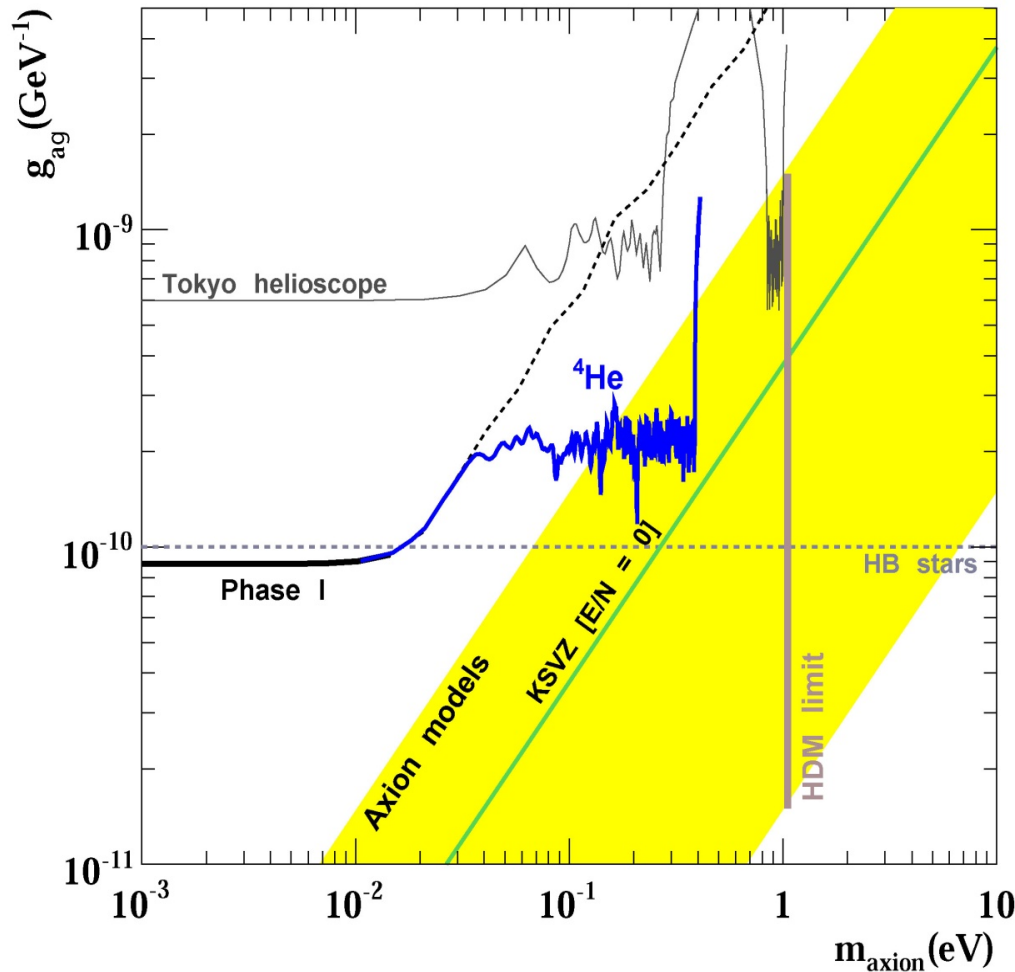
$$\text{for } m_a < 0.02 \text{ eV}$$

- The best experimental limit to date over a large mass range
- Supersedes the best astrophysical limit from Globular cluster HB stars.



# CAST Phase IIa results, using $^4\text{He}$

Arik et al. *JCAP* (2009) 008



## Phase IIa: (2005 – 2006) $^4\text{He}$ operation

- Pressure settings up to 13.4 mbar (160 steps)

$$g_{a\gamma\gamma} < 2.17 \times 10^{-10} \text{ GeV}^{-1} \text{ (95\% CL)}$$

$$\text{for } 0.02 \text{ eV} < m_a < 0.39 \text{ eV}$$

- Starts to exclude interesting QCD model parameter space



# LLNL contributions to CAST

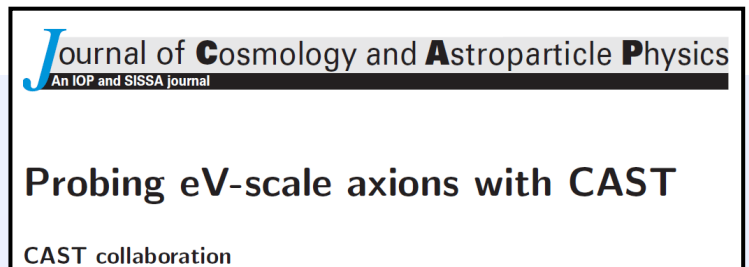
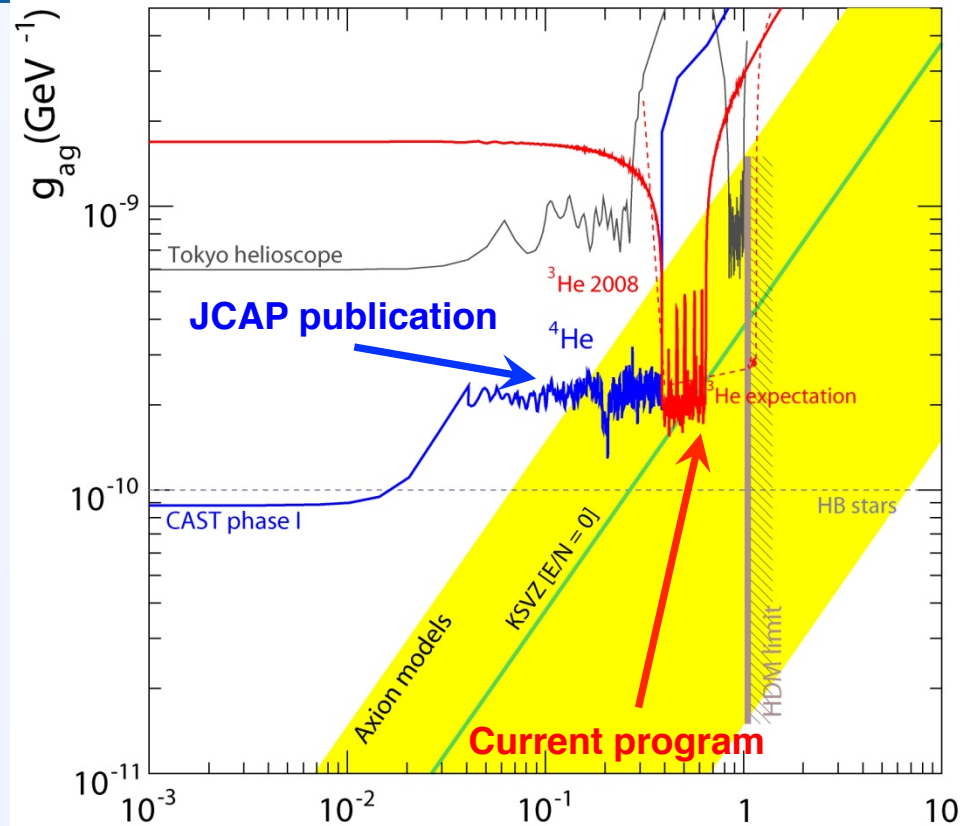
- LLNL's participation funded through two different LDRD programs

## 2004-2007; Novel x-ray optics

- Design, built and calibrated x-ray optic
- Arranged loan of He-3 for phase II

## 2008-2012; Rare event detection

- Scientific leadership
- Hired Julia Vogel, CAST PhD student
- Second CAST PhD student hire likely in later 2011
- 2 peer reviewed papers out; several in progress



# Next Generation Axion Helioscope

- CAST has enough sensitivity to search a narrow region of “traditional” QCD axion phase-space

- Limits set by experimental parameters 
$$g_{a\gamma} \propto \frac{b^{1/8}}{t^{1/8} (B \times L)^{1/2} A^{1/2}}$$

**$b$  = background**

**$B$  = magnetic field**

**$L$  = magnet length**

**$t$  = observation time**

**$A$  = magnet cross-sectional area**

- A carefully designed new experiment could:
  - Dramatically improve sensitivity for higher-mass axion phase space, complimentary to microwave cavity searches
  - Provide data to challenge and test a growing number of models, motivated by astrophysics, that invoke axion-like particles (ALPs)



## Experimental requirements for a new program

- 3 hardware components drive the sensitivity of an axion helioscope: magnet, detectors and optics
- Recast coupling constant dependence to show how each element influence overall sensitivity

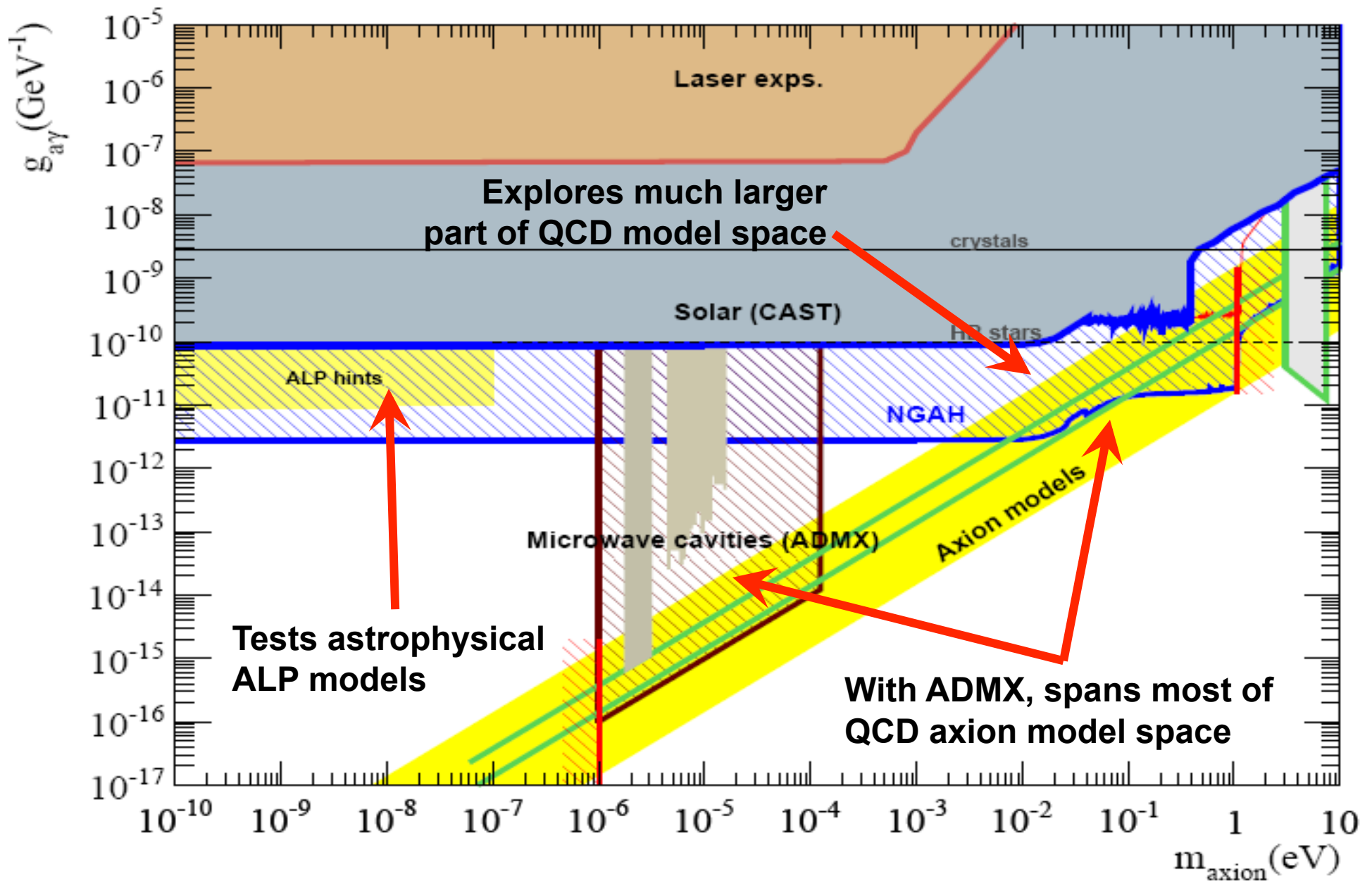
$$\frac{1}{\text{FOM}} \propto g_{a\gamma}^4 \propto \underbrace{b^{1/2} \epsilon^{-1}}_{\text{detectors}} \times \underbrace{a^{1/2} \epsilon_o^{-1}}_{\text{optics}} \times \underbrace{(BL)^{-2} A^{-1}}_{\text{magnet}} \times \underbrace{t^{-1/2}}_{\text{exposure}}$$

- Magnet is the most important lever**

Factor	NGAH vs CAST	Improvement in $g_{a\gamma}^4$
Detector	Background 20× lower	4.5
Optics	Optics 2×more efficient	1.4
Observation time	3 years, 7 hr days instead of 2 years, 1.5 hr /day	2.6
Magnet	Field 50% lower, magnet 2×longer, 1000×more area	1000



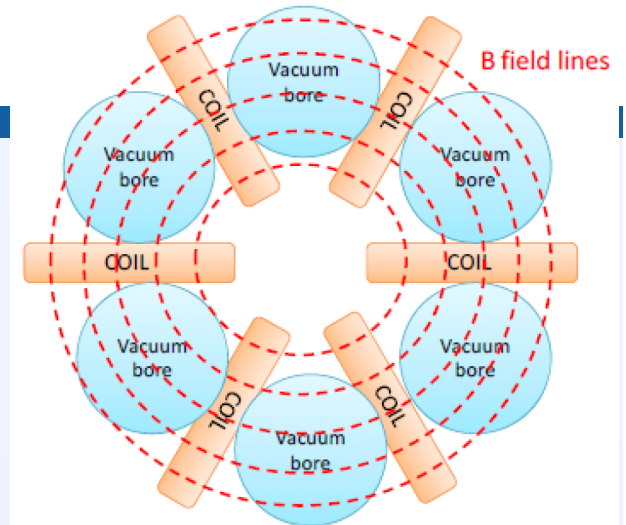
# Potential reach of a new program



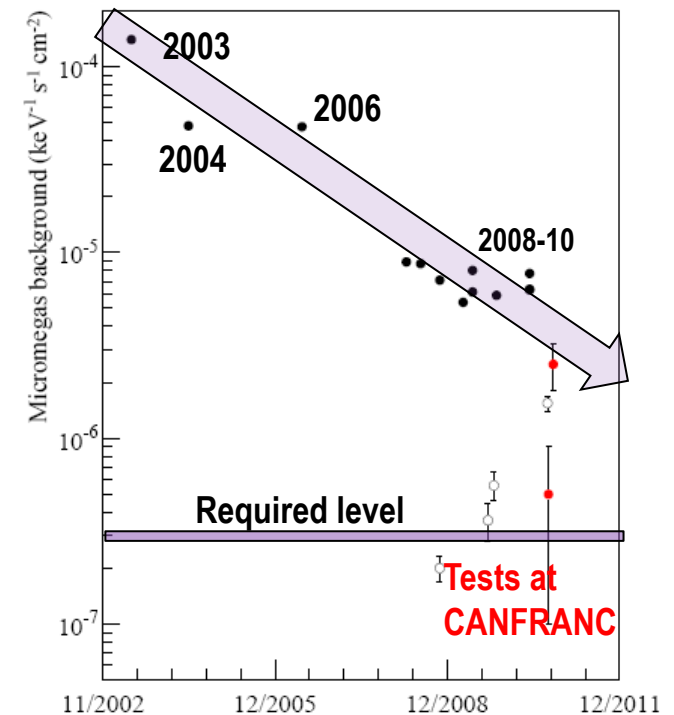
# New collaboration

- Builds on CAST team and will require participation and support from Europe, US and CERN
- Hundred million dollar class experiment
- **Magnet:** ATLAS magnet is point-of-departure (~\$25 – 50M)
  - CERN
  - US: Fermilab? LBNL?
- **Civil & project engineering:** Dedicated facility and building (~\$15 – 25M)
  - US: LLNL
- **X-ray optics**
  - US: Columbia U., LLNL, NASA?
  - MPE/Germany
- **Detectors**
  - CEA Saclay, U. Zaragoza (Spain)
- **Theory**
  - US and Europe

## Cross section of the magnet

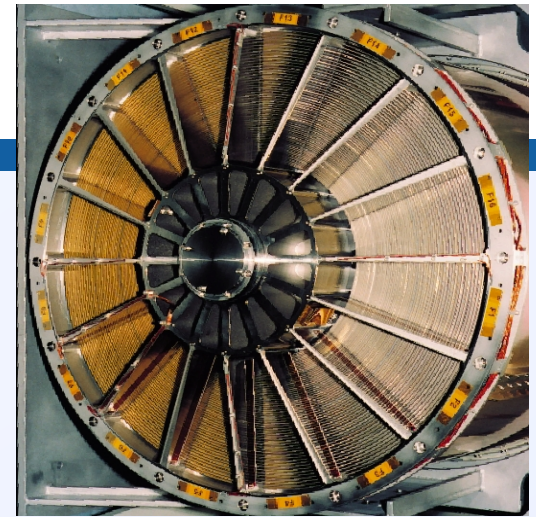


## Improved background performance for Micromegas

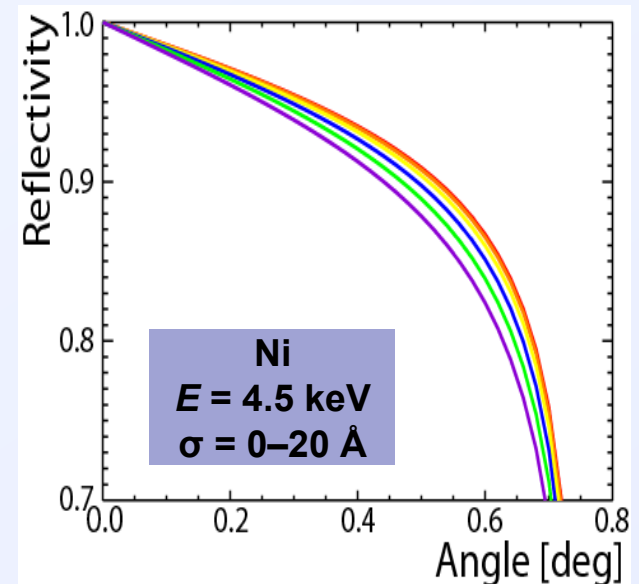


# X-ray optics

- During the last four decades, the x-ray astronomy community has devoted billions of dollars to develop reflective x-ray optics
- Innovations include:
  - Nested designs (so called Wolter telescopes)
  - Low-cost substrates
  - Highly reflective coatings
- Although NGAH will require fabrication of dedicated optics, it will be crucial to **leverage** as much infrastructure as possible to minimize cost and risks



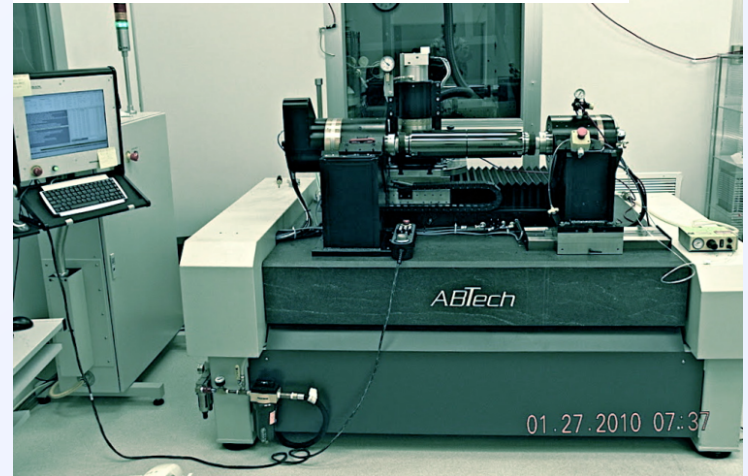
*XMM-Newton* telescope  
with 56 nested shells



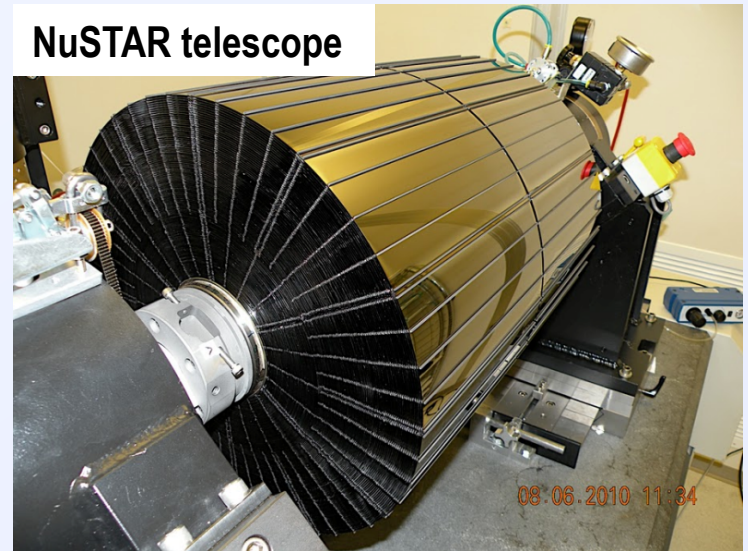
## One possibility: thermally-formed glass substrates

- NASA is currently building NuSTAR, a hard x-ray telescope, using thermally formed glass substrates
- Optics developed by Columbia U. (PI institute), LLNL and others during last decade
- The specialized tooling to shape the substrates and assemble the optics will be available after NuSTAR is launched in 2012
- Hardware can be easily configured to make optics with a variety of designs and sizes
  - LLNL and Columbia already in discussions

NuSTAR optics assembly machine



NuSTAR telescope





# Plans and timelines

- Socialization with European and US federal agencies, CERN and ASPERA starts in 2010
- Magnet studies
  - Build on work already begun at CERN
- Near-term R&D
  - Optics
  - Detectors
- Near-term engineering
  - Sufficient rigor to develop a realistic and safe design for scientific evaluation and CD0

